

*A Practical Approach to  
Transesophageal  
Echocardiography*

Third Edition



# *A Practical Approach to Transesophageal Echocardiography*

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2001 Market Street  
Philadelphia, PA 19103 USA  
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Printed in China

#### **Library of Congress Cataloging-in-Publication Data**

A practical approach to transesophageal echocardiography / editors, Albert C. Perrino, Jr.,  
Scott T. Reeves. – 3rd ed.

p. ; cm.

Includes bibliographical references and index.

ISBN 978-1-4511-7560-8 (alk. paper)

I. Perrino, Albert C. II. Reeves, Scott T.

[DNLM: 1. Echocardiography, Transesophageal—methods. 2. Heart Diseases—ultrasonography.

WG 141.5.E2]

616.1'207543—dc23

2013016039

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*To Anita, Mary, Isabella, and Juliana for sustaining another of my adventures and to Winston Churchill whose keen observation also served as a source of support.*

*Writing is an adventure. To begin with, it is a toy and an amusement. Then it becomes a mistress, then it becomes a master, then it becomes a tyrant. The last phase is that just as you are about to be reconciled to your servitude, you kill the monster and fling him to the public. —Winston Churchill, ACP*



*To My Savior, Jesus Christ, who gives me strength...  
My wife, Cathy, who loves and puts up with me...  
My children, Catherine, Carolyn, and Townsend, who give me great joy...  
My patients, who inspire me to do my best daily! — STR*

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## Preface

**THE THIRD EDITION OF** *A Practical Approach to Transesophageal Echocardiography* represents a remarkable transformation for the highly regarded textbook. Most recognizable is that this edition has been extensively reformatted and published as both an e-book and a portable manual. The e-book format takes full advantage of the possibilities now available to clinicians with both tablet and personal computers. Readers now experience full-motion video and extensive color artwork seamlessly embedded into each chapter. To complete this transformation, the editors have recruited a new team of contributing authors who are internationally renowned and acknowledged for their independent contributions and teaching ability. These authors were given the task of presenting a highly readable and clinically relevant survey of the current practice of perioperative echocardiography. The editors are humbled by the “dream team” of talent drawn to this project. Their enthusiasm, backed with the strong support of the publisher, has produced this book.

There is a charm, and appropriately the third edition includes a feature chapter on three-dimensional (3D) echocardiography. The uses of 3D techniques are embedded throughout the specific topic chapters, particularly, its use during mitral valve surgery. A new chapter provides an up-to-date tutorial on the use of echocardiography during mitral repair. In addition, the expanding use of echocardiography for percutaneous valve procedures has resulted in a dedicated chapter addressing this field. The evolving role of TEE during coronary revascularization, including assessment of ventricular assist devices and TEE's critical role in clinical decision making, has resulted in a new chapter covering these topics.

The reader is guided through the physics, principles, and applications of two-dimensional (2D) imaging and Doppler modalities for assessing ventricular performance and the clinical significance of valvular disease. Updated practice guidelines by the American Society of Echocardiography (ASE), the Society of Cardiovascular Anesthesiologists (SCA), and the European Association of Echocardiography for assessment of valves and ventricles are discussed. Each chapter concludes with 20 self-assessment test questions to further emphasize important teaching points.

Despite the notable comprehensive reference texts and case atlases available on this subject, this edition further establishes the reputation of *A Practical Approach to Transesophageal Echocardiography* as the practicing clinician's premiere resource to acquire the essential skills of TEE practice. The third edition is not a mere refresh of its predecessor but a thoroughly updated manual supported by extensive original color illustrations, figures, and full-motion echocardiographic images. The presentation, media, and content create a surprisingly portable text (both on tablet and as a printed handbook) that is conducive to rapid appreciation of the critical elements in the use of TEE for a particular clinical challenge.

Certainly, the skills required to be an expert echocardiographer cannot be gained from textbooks alone. In addition to clinical-based training, we recommend the excellent educational programs on intraoperative TEE sponsored by the ASE, the SCA, the American Society of Anesthesiologists, and the European Association of Cardiothoracic Anesthesiologists.

We hope this textbook will become a well-worn and valued asset to your echocardiography practice.

*Albert C. Perrino, Jr., MD*  
*Scott T. Reeves, MD, MBA, FACC, FASE*



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# ESSENTIALS OF 2D IMAGING

## 1 Principles and Technology of Two-dimensional Echocardiography

Andrew Maslow and Albert C. Perrino, Jr.

**TWO-DIMENSIONAL ECHOCARDIOGRAPHY GENERATES DYNAMIC IMAGES** of the heart from reflections of transmitted ultrasound. The echocardiography system transmits a brief pulse of ultrasound that propagates through and is subsequently reflected from the cardiac structures encountered. The sound reflections travel back to the ultrasound transducer, which records the time delay for each returning reflection. Since the speed of sound in tissue is constant, the time delay allows for a precise calculation of the location of the cardiac structures from which the echocardiography system can then create an image map of the heart. Not surprisingly, successful cardiac imaging requires a firm understanding of the interactions of sound and tissue. This chapter reviews the basic principles of ultrasound, its propagation through tissues, and the technologies which create moving images of the heart.

### PHYSICAL PROPERTIES OF SOUND WAVES

#### Vibrations

Sound is the vibration of a physical medium. In clinical echocardiography, a mechanical vibrator, known as the *transducer*, is placed in contact with the esophagus (transesophageal echocardiography [TEE]), skin (transthoracic echocardiography), or the heart (epicardial echocardiography) to create tissue vibrations. The resulting tissue vibrations or sound waves consist of areas of *compression* (areas where molecules are tightly packed) and *rarefaction* (areas where molecules are dispersed) resembling a sine wave (Fig. 1.1).

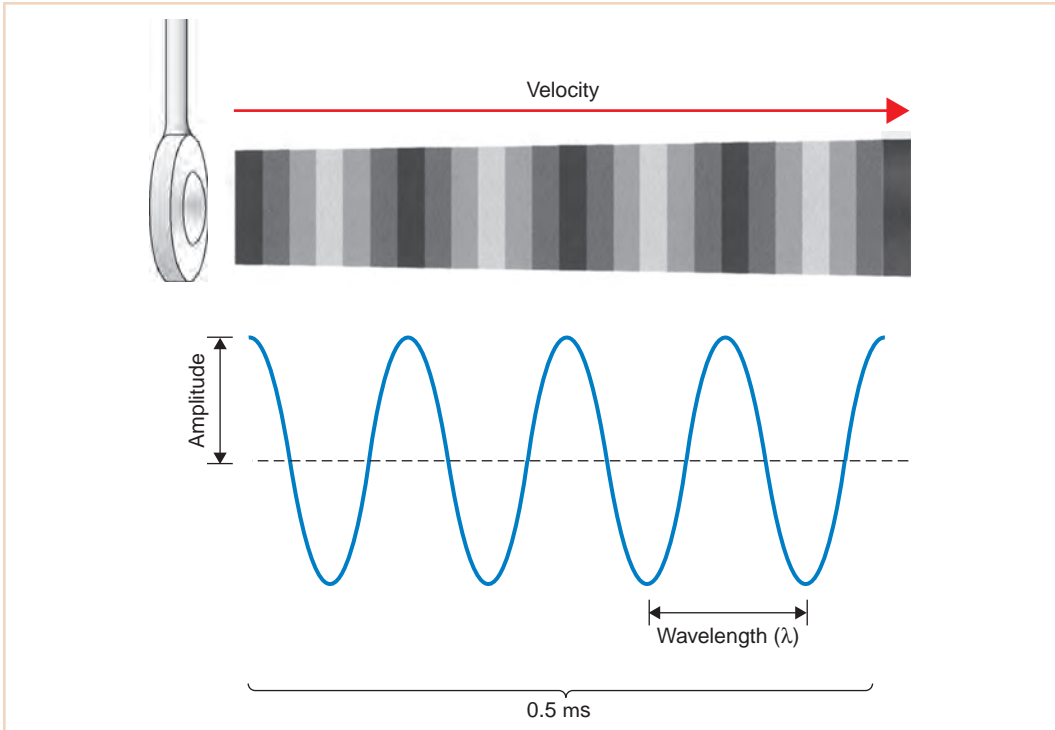
#### Amplitude

The amplitude of a sound wave represents its peak pressure and is appreciated as loudness. The level of sound energy in an area of tissue is referred to as *intensity*. The intensity of the sound signal is proportional to the square of the amplitude and is an important factor regarding the potential for tissue damage with ultrasound. For example, lithotripsy uses high-intensity sound signals to fragment renal stones. In contrast, cardiac ultrasound uses low-intensity signals to image tissue, which produces only limited bioeffects. Since levels of sound pressure vary over a large range, it is convenient to use the logarithmic decibel (dB) scale:

$$\begin{aligned}\text{Decibel (dB)} &= 10 \log_{10} I/I_r = 10 \log_{10} A^2/A_r^2 \\ &= 20 \log_{10} A/A_r\end{aligned}\tag{1}$$

where  $A$  is the measured sound amplitude of interest and  $A_r$  is a standard reference sound level,  $I$  is the intensity and  $I_r$  is a standard reference intensity.

More simply expressed, each doubling of the sound pressure equals a gain of 6 dB. The U.S. Food and Drug Administration (FDA) limits the maximum intensity output of cardiac ultrasound systems to be less than  $720 \text{ W/cm}^2$  due to concerns with possible tissue and neurologic damage from mechanical injury (resulting from cavitation or microbubbles caused by rarefaction) and thermal effects. The



**FIGURE 1.1** Sound wave. Vibrations of the ultrasound transducer create cycles of compression and rarefaction in adjacent tissue. The ultrasound energy is characterized by its amplitude, wavelength, frequency, and propagation velocity. In this example, four sound waves are shown in a period of  $0.5 \mu\text{s}$ . The frequency can be calculated as 4 cycles divided by  $0.5 \mu\text{s}$  and equals 8 MHz.

ALARA principle recommends that clinicians use exposure levels As Little As Reasonably Achievable to protect patients.

### Frequency and Wavelength

Sound waves are also characterized by their *frequency* ( $f$ ), or pitch, expressed in cycles per second, or Hertz (Hz), and by their *wavelength* ( $\lambda$ ). These attributes have a significant impact on the depth of penetration of a sound wave in tissue and the image resolution of the ultrasound system.

### Propagation Velocity

The *travel velocity* or *propagation velocity* of sound ( $v$ ) is determined solely by the medium through which it passes. For example, the speed of sound in soft tissue is approximately 1,540 m/s. Velocity can be calculated as the product of wavelength and frequency:

$$v = \lambda \times f \quad (2)$$

It becomes apparent that the wavelength and frequency are necessarily inversely related:

$$\lambda = v \times 1/f \quad (3)$$

$$\lambda = (1500 \text{ m/s})/f \quad (4)$$

Table 1.1 lists the corresponding sound wavelengths and frequencies commonly used in clinical ultrasonography.

**TABLE 1.1** Corresponding Frequencies and Wavelengths in Soft Tissue

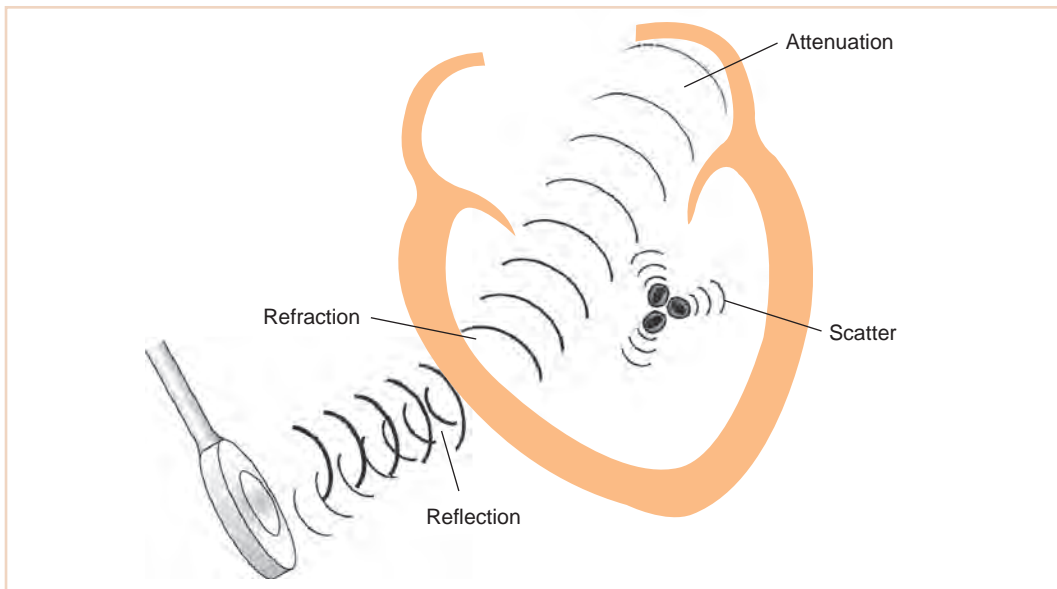
Frequency (MHz)	Wavelength (mm)
1.25	1.20
2.5	0.60
5	0.30
7.5	0.20
10	0.15

## WHAT IS SO SPECIAL ABOUT ULTRASOUND?

Several favorable physical properties of ultrasound explain its usefulness in clinical imaging. *Ultrasound* is sound with frequencies greater than those of the audible range for humans (20,000 Hz). In clinical echocardiography, frequencies of 2 to 10 MHz are used. The high-frequency, short-wavelength ultrasound beam can be more easily manipulated, focused, and directed to a specific target. Image resolution also increases when higher-frequency sound waves are used (see later).

## INTERACTIONS OF SOUND AND TISSUE

The propagation, or passage, of a sound wave through the body is markedly affected by its interactions with the various tissues encountered. These interactions result in reflection, refraction, scattering, and attenuation of the ultrasound signal. The exact manner in which sound is affected by the various tissues it encounters determines the resulting appearance of the two-dimensional image (Fig. 1.2).



**FIGURE 1.2** Interactions of sound and tissue. Traveling through various tissues, sound energy is altered by four major events. Specular *reflection* creates strong echoes directed back toward the transducer. *Refraction* bends the ultrasound beam directing it in a new path. As the ultrasound beam travels deeper in tissue, *attenuation* occurs as the beam is dispersed and the sound energy is converted to heat. *Scattering* reflections from small objects such as red cells disperse the sound energy in all directions.

**TABLE 1.2** Acoustic Properties of Various Tissues

Tissue/medium	Speed of sound (m/s)	Acoustic impedance (kg/m <sup>2</sup> × 10 <sup>6</sup> )	Attenuation coefficient (cm <sup>-1</sup> at 1 MHz)	Half-power distance (cm at 2.5 MHz)
Air	330	0.00004	—	0.08
Lung	600	0.26	—	0.05
Fat	1,460	1.35	0.04–0.09	—
Water	1,480	1.52	0.0003	380
Blood	1,560	1.62	0.02	15
Muscle	1,600	1.7	0.25–0.35	0.6–1
Bone	4,080	7.80	—	0.7–0.8

## Reflection

Echocardiographic imaging depends on the transmission and subsequent reflection of ultrasound energy back to the transducer. A sound wave propagates through uniform tissue until it reaches another tissue type with different acoustic properties. At the tissue interface, the ultrasound energy undergoes a dramatic alteration, after which it can be reflected back toward the transducer or transmitted into the next tissue, often in a direction that deviates from the original course. Precisely how the ultrasound beam will be affected is predicted by factoring the acoustic properties of the tissues that create the interface and the angle at which the ultrasound beam strikes this interface.

### The Tissue Interface: Acoustic Impedance

An important acoustic property of a tissue is its capacity for transmitting sound, known as *acoustic impedance* ( $Z$ ). This property is largely related to the *density* ( $\rho$ ) of the material and the speed which ultrasound travels ( $v$ ):

$$Z = \rho \times v \quad (5)$$

As seen in Table 1.2, denser materials such as bones and fluids effectively transmit ultrasound, whereas air and lung tissue have a low level of acoustic impedance and are poor transmitters of sound energy. This property explains why an amplification system is required even for a small lecture hall, yet whales can hear sound over great expanses of the ocean.

When sound reaches an interface of two tissues of similar acoustic impedance, the ultrasound beam travels across the interface largely undisturbed. When the tissues differ in impedance, a percentage of the ultrasound energy is *reflected* and the remainder is *transmitted*. *The larger the absolute difference in the levels of acoustic impedance across the interface, the greater the percentage of the ultrasound energy that is reflected.* Reflection can be calculated by using the reflection coefficient ( $R$ ):

$$\text{Reflection coefficient} = \frac{(Z_2 - Z_1)^2}{(Z_1 + Z_2)^2} \quad (6)$$

The reflective properties of an interface are key factors in the imaged appearance of a structure. When the absolute difference between the levels of acoustic impedance of the two interfacing media is large, as when soft tissue interfaces with air or bone, more energy is reflected back to the transducer. These interfaces are represented by echo-dense or bright signals on the echogram. When the absolute difference is small, as when soft tissue interfaces with soft tissue, the interface will not appear as bright and may even be echolucent or dark.

### Specular and Scattering Reflectors

The reflection of sound is also greatly affected by the size and surface of the tissue. Two types of reflection, specular and scattered, are commonly encountered.

*Specular reflection* occurs when a sound wave encounters a large object with a smooth surface. Such surfaces act like an acoustic mirror, generating strong reflections that travel away from the interface at an angle equal and opposite to that at which the ultrasound beam traveled to the interface. Reflection is maximal when the angle of incidence is 90 degrees—that is, the ultrasound beam and the object are perpendicular to each other. With an angle of incidence other than 90 degrees, less energy is reflected back to the transducer. Because of the important effect of strong specular reflection on image quality, echocardiographers adjust the position of the TEE transducer so that the direction of its beam is perpendicular to the cardiac structure of interest.

*Scattering reflection* occurs when an ultrasound beam encounters small or irregularly shaped surfaces. Such small objects, such as red blood cells, scatter ultrasound energy in all directions, so that far less energy is reflected back to the transducer than in the case of a specular reflector. This type of reflection is the basis of the Doppler analysis of red blood cell movement.

*Both types of reflection contribute to the two-dimensional image.* Although the strongest signals and best images are obtained from interfaces that are perpendicular to the beam orientation, cardiac tissue is to a large extent irregular and nonlinear in shape. Therefore, a significant component of the reflected energy comes from scattering off the smaller irregular components of tissue. An example is imaging of the lateral and septal walls of the left ventricle from esophageal windows. Although the ventricular walls are parallel to the ultrasound beam, they can be imaged as a result of both specular reflection and scattering off the irregular surfaces of the myocardium. However, the total amount of ultrasound returning to the transducer is low, which accounts for the poor quality of images, which often include dark spots called *echo dropout*. Adjusting the transducer angle or using a different echocardiographic window to orient the beam more perpendicular to the structure of interest will often dramatically improve image quality.

## Refraction

The portion of the ultrasound beam that is not reflected propagates through the interface, but its direction is often altered or refracted. Refraction is most pronounced when the difference in sound velocities in the two tissues is large and the angle of incidence is acute. When the angle of incidence is 90 degrees, or when the difference in levels of acoustic impedance is minimal, refraction does not occur because the ultrasound energy is either reflected or continues to travel in the same direction.

Refraction is an important factor in the formation of artifacts. Although the ultrasound beam may proceed in an altered direction, the transducer does not recognize this change.

Consequently, the refracted energy may interface with a cardiac structure outside the *intended* scanning field. The reflected energy from this interface returns to the transducer, which then incorrectly displays the structure alongside structures detected by the beam in its original course (Fig. 1.3). Altering the viewing angle so that the ultrasound energy is perpendicular to the area of interest minimizes refraction and any resultant artifact.

## Attenuation

In addition to being reflected and refracted from tissue interfaces, the ultrasound signal is altered as it travels through uniform tissue. Most notable is the steady loss (i.e., attenuation) in transmitted intensity as a consequence of dispersion and absorption. The attenuation in ultrasound energy caused by dispersion and absorption result in less energy returning to the transducer, and subsequently a weaker signal on the display with a poor signal-to-noise ratio.

*Dispersion* occurs as the ultrasound beam diverges over a greater area in the far field. In addition, since the cellular structure of tissue is irregular, scattering further disperses the ultrasound energy. The amount of scattering varies greatly with tissue type.

*Absorption* occurs as frictional forces convert ultrasound energy into heat. Since friction is related to the level of tissue movement, it is not surprising that the higher the frequency of the signal and the greater the distance traveled, the greater the absorption (Fig. 1.4). The dependence of attenuation on frequency and distance is reflected in the *attenuation coefficient* (dB/cm/MHz), which allows for a comparison of the degree of attenuation between tissue types. The penetration of ultrasound can also be expressed by the *half-power distance* specific for each tissue, which expresses the distance sound will travel until half of its original energy is lost. The acoustic properties of various tissues are summarized in Table 1.2.